Spectrally Tunable Solid-State Light Source

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Abstract

A low-cost, spectrally tunable, solid-state light source has been developed for testing and calibration of digital still camera (DSC) products in the design and production environments. The light source utilizes LEDs with a plurality of unique emission spectra to synthesize visible range spectra with independent control of both spectral shape and output level. This technology obviates the need for physical color targets and their requisite lighting, thereby enabling low-cost, accurate colorimetric calibration of each DSC in the production environment. This paper summarizes the colorimetric performance of this light source relative to other commonly used light sources and to published CIE metrics.

Introduction

In recent years, competitive pressures in the DSC marketplace have forced manufacturers to rethink many aspects of their business, including expenditures for capital equipment used in the production process. Eastman Kodak Company responded to this internal need by initiating a program to develop standardized production test equipment that could be leveraged across multiple DSC programs and many years of use. In the past, such equipment was developed for a specific program and then discarded upon program completion. The new approach would allow reuse of major capital assets through a combination of interchangeable mechanical "nests" and reconfigurable software and firmware.

One of the nagging problems also facing the DSC production community was the lack of availability of a suitable light source to meet the needs for camera calibration and image quality testing while eliminating the undesirable attributes of warm-up time, frequent bulb replacement, daily calibration and monitoring, poor spectral quality, and lack of repeatability from one light source to the next. A solid-state light source concept, using LEDs, was proposed and developed to satisfy this need. The newly developed light source also fit well within the reconfigurable capital equipment strategy by providing independent programmability of spectral shape and output level as well as multiple operating modes to support different types of imagers. Construction and operational details of this light source are disclosed in U.S. patent 6,759,814. The latest models of this light source in use at Kodak feature only 12 unique LED channels having the emission spectra summarized in Fig. 1.

Desired visible band spectra are synthesized by suitable combinations of the available LED spectra. The spectral mixing process can be described in its most basic form by Eqs. (1) and (2).

$$\mathbf{a} = \left(\mathbf{LED}^T \cdot \mathbf{LED}\right)^{-1} \cdot \mathbf{LED}^T \cdot \mathbf{SPD} \qquad (1)$$

$$\mathbf{src} = \mathbf{a} \cdot \mathbf{LED} \qquad (2)$$

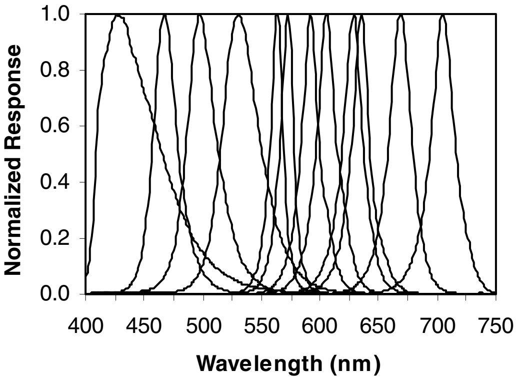

***Figure 1**. Summary of LED spectra used in the spectrally tunable, solid-state light source.*

LED is a 12 × 351 array containing the spectral radiance data for the 12 LEDs. This data covers the range from 400 to 750 nm in 1 nm increments and is measured at the interior sphere wall. **SPD** is a 1 × 351 vector containing the spectral power distribution data for the source that is to be synthesized. The result from Eq. (1) is a 1 × 12 vector **a** containing the relative contributions of each LED channel required to accurately synthesize the desired SPD. The synthesized output **src** is obtained by multiplying these coefficients times the original LED spectra according to Eq. (2). In practice, the coefficients are used to modulate the relative on-times of the LED channels. Figure 2 shows a comparison of an actual D_{55} illuminant SPD and the synthesized output according to Eqs. (1) and (2).

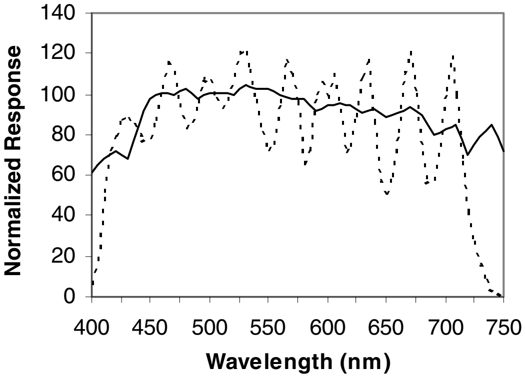

***Figure 2**. Actual (solid) and synthesized (dotted) D_{55}.*

Others have demonstrated that it is possible to obtain a much better spectral match by including LEDs with many more unique wavelengths [1,2]. However, because of schedule and development cost constraints, the current project was executed using LEDs of known character that had previously been selected by another product program.

Colorimetric Performance

Early in the investigative phase of the solid-state light source development, it was not apparent that this technology would be suitable for colorimetric work, as evidenced by the poor spectral match between the synthesized and desired SPDs (see Fig. 2). Evaluations were performed using simulated solid-state light source data to assess the expected performance against the following metrics:

- Correlated color temperature (CCT)
- Visible range metamerism index (MI$_{vis}$)
- Color-rendering index (CRI)
- CIELAB ΔE*

Simulations were also performed to determine the expected performance of the solid-state light source when used in conjunction with an actual digital still camera for the purpose of colorimetric calibration. Several different types of light source were already in use in DSC production environments within the company, therefore, it was determined to also include them in the evaluation. Three sources suitable for illuminating a reflective chart were chosen, as summarized below.

- ARRI Compact 200 HMI
- Solax daylight simulator (filtered Xenon)
- Kinoflo 152-K55-S (fluorescent lamp)

Each of the selected sources had a nominal correlated-color temperature aim of 5500 K. The following sections briefly describe each of the performance metrics used and the results for each light source considered.

Correlated Color Temperature (CCT)

The fourth edition of the CIE International Lighting Vocabulary defines the correlated color temperature as follows: "Temperature of the Planckian radiator whose perceived colour most closely resembles that of a given stimulus seen at the same brightness and under specified viewing conditions. The recommended method of calculating the correlated colour temperature of a stimulus is to determine on the *u,v* (not the *u',v'*) chromaticity diagram the temperature of the point on the locus of Planckian radiators that is nearest to the point representing the stimulus" [3].

The correlated color temperature was computed for each of the light sources under consideration using the method outlined by Wyszecki and Styles [4]. The results are summarized in Table 1 and shown graphically in Fig. 3. The LED-based source was within 150 K of the D$_{55}$ aim, while the Solax and ARRI sources were both approximately 500 K away from the aim in opposite directions. The Kinoflo lamp was almost 1,300 K higher than its published color temperature, leading us to question whether it was being operated correctly. Unfortunately, there was no opportunity to have the spectral data measured again. Figure 3 illustrates that the chromaticities of the solid-state source fall essentially on the D-illuminant locus, whereas the chromaticities of the other sources are somewhat distant from the locus.

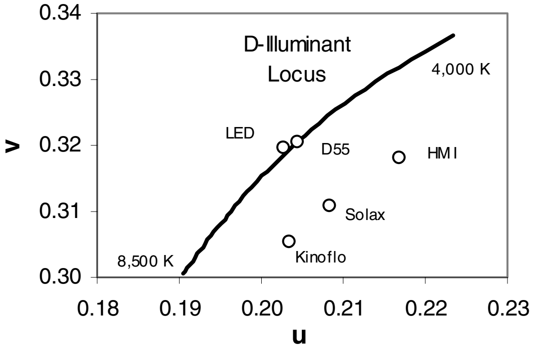

Figure 3. Location of the evaluated light sources relative to the D-illuminant locus.

Color-Rendering Index (CRI)

CIE Technical Report 13.3 (1995) provides a method of assessing the color rending properties of a particular light source relative to a D-illuminant having the same color temperature [5]. Assessment is based on a set of eight Munsell colors to arrive at an average color-rendering index that ranges in value from 0 to 100. Sources with a color-rending index of 100 are considered to be equivalent to a D-illuminant of the same color temperature. The CRI for each source was computed and summarized in Table 1, where each source is ranked in order of descending CRI value.

Visible Range Metamerism Index (MI$_{vis}$)

CIE Publication 51, TC-1.3 (1981), provides a method for assessing the suitability of a particular light source as a simulator of D-illuminants D$_{55}$, D$_{65}$, or D$_{75}$ [6]. Two metamerism indices are defined—one for the visible range (MI$_{vis}$) and one for the ultraviolet range (MI$_{uv}$)—and the assessment is based on different sets of metameric samples for each index. For the current evaluation, only the visible metamerism index is considered for comparison with illuminant D$_{55}$. Five performance categories, ranging from A to E, are defined based on the CIELAB ΔE* value computed for the metamerism index. The visible range metamerism index, and corresponding source category, were computed for each source, and the results are summarized in Table 1.

Table 1. Light Source Performance Metrics

Source	CCT (K)	CRI	MI*vis* (ΔE*)	Category
D$_{55}$	5502	100	0.00	A
LED	5640	98	0.41	B
HMI	4974	96	0.76	C
Solax	5947	94	0.36	B
Kinoflo	6792	91	0.79	C

Both the solid-state and Solax sources received MI_{vis} values below 0.5 ΔE* units, placing them into category B. Even though the HMI source had a visible range metamerism index that was double that of the Solax source, it will be shown later that it actually performed better for calibrating a DSC.

Illuminant/Color Patch Spectral Synthesis

An area of particular interest is the ability of the solid-state light source to accurately synthesize a set of spectra as might be represented by the SPD of a particular source or illuminant concatenated with the spectral reflectance characteristics (SRD) of a color chart comprising a plurality of color patches. For this exercise, a Macbeth Color Checker (MCC) was chosen because its characteristics are already familiar to the worldwide image science community.

An aim data set was created by first calculating the CIE XYZ tristimulus values for each patch of the MCC under a 5500 K D-illuminant. The D-illuminant SPD was calculated at 5 nm increments over the range from 400 to 700 nm. The XYZ values were then transformed to CIELAB L*, a*, and b* values. Reproduction data sets for the ARRI, Solax, and Kinoflo sources were created using the same procedure. The average and maximum CIELAB ΔE* values were computed from the aim and reproduction data sets, and the results are summarized in Table 2.

A reproduction data set was created for the solid-state light source by first concatenating the actual D_{55} SPD with the MCC reflectance spectra followed by synthesis of the combined spectra using Eqs. (1) and (2). XYZ values were then computed from the synthesized D_{55}/MCC spectra with normalization performed relative to the synthesized D_{55} SPD (Fig. 2). The average and maximum CIELAB ΔE* values were computed from the aim and reproduction data sets, and the results are summarized in Table 2.

Table 2. Color Performance of Light Sources

Source	ΔE*ave	ΔE*max
LED	0.61	2.34
Solax	1.51	3.62
HMI	1.94	5.77
Kinoflo	2.12	5.90

Again, the solid-state light source fared better than did the other three sources in reproducing the colorimetry of the color chart when compared to illuminant D_{55}. However, it is important to note that in this case the solid-state light source is actually synthesizing the spectra of the source/color patch combinations, thereby replacing the physical color chart entirely.

DSC Calibration Results

Perhaps the most important performance criterion for the solid-state light source is its ability to enable accurate calibration of a DSC's white-balance gains and color-correction matrix so that the DSC performs correctly when used under the intended illumination conditions. A set of spectral sensitivities for a typical KODAK Blue Plus Color Image Sensor, combined with a dichroic infrared (IR) filter, were chosen to serve as the basis for this evaluation, as shown in Fig. 4. A set of Guassian spectral sensitivities is also shown and will be discussed later.

A set of RGB values for each of the 24 MCC color patches were computed by concatenating the SPD of the selected source with the SRD of each color patch and the spectral sensitivities of the imager, and then the results were summed for each wavelength within each color channel. The spectral sensitivities were first normalized to produce equal RGB values for the SPD alone, equivalent to white-balancing the camera. This process was repeated for each of the sources, including illuminant D_{55}. For the solid-state light source, the resulting synthesized spectra for each SPD/SRD combination were concatenated with the sensitivities of the imager to compute the RGB values. In this case, the spectral sensitivities were normalized to produce equal RGB values for the synthesized D_{55} illuminant alone (see Fig. 2).

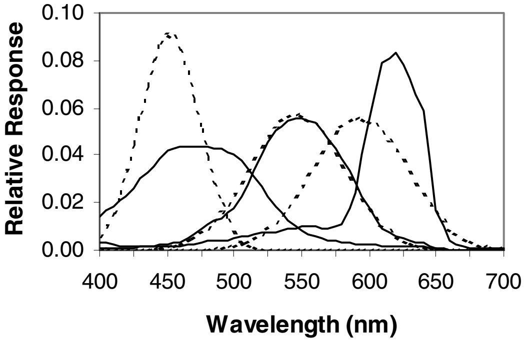

***Figure 4**. Comparison of CCD (solid) and Guassian (dotted) spectral sensitivities (all normalized to unit area).*

Color-correction matrices were computed for each case using a process described in U.S. patent 5,668,596, with chromatic adaptation applied and error minimization performed in the CIELAB color space. The average and maximum CIELAB ΔE* values were computed for each case and are summarized in Table 3. The white-balance errors, expressed as a red/green or blue/green ratio, were also computed and are summarized in Table 3. These errors represent the result of calibrating the DSC with the indicated source and then using it under actual D_{55}.

Table 3. Colorimetric Performance of Light Sources with the KODAK Blue Plus Color Image Sensor

Source	R/G Error (%)	B/G Error (%)	ΔE*ave	ΔE*max
D_{55}	0.00	0.00	3.33	10.95
LED	-0.14	0.52	3.21	10.11
HMI	7.17	0.20	3.72	12.00
Solax	4.20	13.26	3.78	13.33
Kinoflo	3.03	16.94	4.13	15.76

The results in Table 3 show that a DSC that is calibrated using the solid-state light source will exhibit small white-balance errors when used under actual D_{55}. The other sources will cause much larger white-balance errors to be present. It is interesting to note that there is not much difference in the average color error when any of the sources are used for colorimetric calibration. This is a result mainly of the quality of the spectral sensitivities of the imager itself.

To test this hypothesis, a set of RGB spectral sensitivities were computed that were close to color-matching functions (CMFs). A particular set of spectral sensitivities is defined to be a set of CMFs if there exists a 3 × 3 linear transformation that relates them to the spectral sensitivities of the human visual system. The colorimetric quality factor (CQF) metric, proposed by Neugebauer, was used to guide the derivation of this set of spectral sensitivities [7]. Spectral sensitivities that are CMFs will have a CQF value of unity, and those that depart from CMFs will have a CQF value of less than unity. A Guassian curve shape was chosen because it is easy to generate mathematically and the actual spectral sensitivities (see Fig. 4) were computed using Eq. (4) based on the parameters summarized in Table 4. The CQF value for each of the actual CCD imager channels is also included for comparison.

$$S_\lambda = \exp\left[\frac{-4\cdot\ln(0.5)}{b^2}\cdot(\lambda-\lambda_{PK})\right] \qquad (4)$$

Table 4. Parameters for Guassian Sensitivities

Channel	λ_{PK} (nm)	*b* (nm)	CQF*	CQF**
Red	593	84	0.997	0.715
Grn	546	82	0.998	0.996
Blu	451	53	0.993	0.827

** Guassian, ** CCD*

The DSC evaluation process described in conjunction with Table 3 was repeated for the DSC having Guassian spectral sensitivities with the results summarized in Table 5.

Table 5. Colorimetric Performance of Light Sources with Imager Having Guassian Sensitivities

Source	R/G Error (%)	B/G Error (%)	ΔE*ave	ΔE*max
D_{55}	0.00	0.00	0.29	0.88
LED	–1.21	0.58	0.35	1.04
HMI	9.56	6.18	0.83	2.85
Solax	2.79	21.83	1.77	4.57
Kinoflo	–1.86	29.69	3.04	8.57

Note that there is still a small residual average color error when the DSC is calibrated using illuminant D_{55}, and then used under the same illuminant. This result is not unexpected because the Guassian sensitivities are not exactly CMFs. The average color error is only slightly worse for the solid-state light source, however, the HMI, Solax, and Kinoflo sources exhibit progressively larger average color errors. The white balance errors are again small when the solid-state light source is used, however, much larger errors are evident for the other three light sources.

Summary

The solid-state light source has been shown to outperform several other commonly used light sources in every test category. These results were not readily apparent at the onset of the development program and are actually quite surprising considering that only 12 unique LED spectra were used. Others have demonstrated that this performance can be improved further using LEDs with more unique spectra [1,2].

Direct synthesis of visible band spectra has enabled the replacement of physical color targets and their requisite lighting for DSC colorimetric calibration. The small size and relatively low cost of the solid-state light source, in addition to its accuracy, reliability, and stability, have made it economically feasible to introduce individual colorimetric calibration even into cost-sensitive DSC production environments.

References

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Biography

Richard Vogel received both his Bachelor’s degree in Electrical Engineering and his Master’s degree in Imaging Science from the Rochester Institute of Technology. He joined Eastman Kodak Company in 1983 and has worked on numerous electronic imaging products in roles including hardware design, image-processing algorithm development, color calibration, and development of specialized test equipment and methods for digital still camera production. He holds 13 patents and is currently a member of the Corporate Engineering Division.